Optical and VLF Imaging of Lightning-Ionosphere Interactions

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LONG-TERM GOALS

This work addresses some of the key topics of space physics research recommended in the National Research Council 2003 report "A Decadal Research Strategy in Solar and Space Physics," namely, the thunderstorm-driven electrodynamic coupling between the troposphere, mesosphere, lower ionosphere, and magnetosphere. Lightning-induced electron precipitation encompasses all of these regions, from atmospheric and mesospheric electrodynamics, to radiation belt scattering, to precipitation and disturbances of ionospheric communication channels. Observation of direct lightning-ionospheric coupling mechanisms such as elves can lead to the understanding of ion chemical dynamics in the upper-mesosphere, lower-ionosphere, including determination of ambient electron density profiles and unknown chemical interaction parameters. Sprites and their possible conjugate effects due to relativistic electrons also constitute a coupling between the regions, including lightning effects on the mesosphere and ionosphere. Geomagnetic disturbances highlight the coupling between these regions, with the resulting perturbations in the magnetosphere and ionosphere easily detectable.

OBJECTIVES

Objectives of the current three-year effort are to address the following scientific questions: How do sprites evolve on a fine spatial and temporal scale, and how does this evolution compare to conventional and streamer breakdown theory? What is the cause of the fine-scale bead-like features of sprites? How does the thundercloud activity relate to the spatial and temporal evolution of sprites? How are sprites and sprite halos related to conductivity perturbations on the ionosphere, observed as early/fast perturbations to VLF transmitter signals? What role do elves play in these ionospheric perturbations? What is the effect of in-cloud lightning on the lower ionosphere? How can VLF remote sensing be used to quantify atmospheric ion-chemistry interaction parameters? Are long-recovering Early VLF events the result of a different causative mechanism than their short-recovery counterparts, and are long recovery events more likely to be observed on all ocean-based paths than paths over land? If so, what is the physical source of this preference? What role do lightning-generated whistlers play in the formation of the slot region of the radiation belts? How can VLF remote sensing be used to quantitatively measure the energy spectra and flux of precipitating electrons associated with LEP events? What is the contribution of MR whistlers and lightning-triggered-plasmaspheric hiss to the loss of electron radiation?

APPROACH

Our approach consists of the use of optical and wideband ELF/VLF measurements to document high altitude optical phenomena such as sprites and elves, and ELF/VLF holographic imaging of

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14. ABSTRACT

This work addresses some of the key topics of space physics research recommended in the National Research Council 2003 report ?A Decadal Research Strategy in Solar and Space Physics,? namely, the thunderstorm-driven electrodynamic coupling between the troposphere, mesosphere, lower ionosphere, and magnetosphere. Lightning-induced electron precipitation encompasses all of these regions, from atmospheric and mesospheric electrodynamics, to radiation belt scattering, to precipitation and disturbances of ionospheric communication channels. Observation of direct lightning-ionospheric coupling mechanisms such as elves can lead to the understanding of ion chemical dynamics in the upper-mesosphere, lower-ionosphere, including determination of ambient electron density profiles and unknown chemical interaction parameters. Sprites and their possible conjugate effects due to relativistic electrons also constitute a coupling between the regions, including lightning effects on the mesosphere and ionosphere. Geomagnetic disturbances highlight the coupling between these regions, with the resulting perturbations in the magnetosphere and ionosphere easily detectable.

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ionospheric disturbances together with the causative lightning flashes. The ELF/VLF antennas are deployed at several high schools and colleges spread across the United States, with the students and teachers at these schools involved in the program as part of our educational outreach efforts. Observations of sprites and elves are also made in the Midwestern United States using high-speed telescopic imaging, low-light cameras, photometric measurements, and ELF/VLF measurements of causative sferics. Sprite and elve observations are compared with VLF narrowband and broadband data to establish correlations between sprite features and lightning and ionosphere activity. The key individuals involved are graduate students that are either fully funded under this program or partly funded by an associated NSF grant, ~10% effort of an engineer, and the Principal Investigator. The students are involved in all aspects of the program, including design and construction of equipment and software, deployment, data acquisition and interpretation, as well as educational outreach (for example by providing lectures at the high schools). The engineer is mainly involved in data archiving and increasing data accessibility.

WORK COMPLETED

A poster presented at the AGU fall conference highlighted the first discovery of backscatter of a VLF transmitter signal by daytime Early/fast events which indicate that lightning (or an as yet unidentified lightning-related event) is capable of producing extremely high levels of ionization ($>10^4$ electrons/cm^3) with exceptionally narrow horizontal extent (i.e. Gaussian width <2 km). In addition, it appears that the source of this backscatter is far more likely to occur during daytime than nighttime.

Ongoing work related to the long recovering Early VLF events is also currently underway. In a paper by *Cotts and Inan* [2007a] it was postulated that the cause of long recovery Early VLF events could be gigantic blue jets. In an effort to confirm this hypothesis an intensified camera with remotely-controlled pointing capability has been deployed at the Arecibo observatory along with a combination broadband/narrowband VLF recording system. The combination of these two systems allows the concurrent recording of optical and VLF signature of a gigantic blue jet. The camera is mounted to a remotely-controllable apparatus capable of turning 360^o in azimuth and 90^o in elevation. Combining the newly deployed VLF receiver at Arecibo (with other supporting VLF sites operated by Stanford), nine VLF transmitter signals whose GCPs (Great Circle Paths) span an azimuth range of $\sim 90^o$ centered at geographic north are now being monitored.

Analysis of PIPER data from the Summer 2007 TLE Observation campaign in Yucca Ridge, CO was completed. Numerous sprites were observed photometrically at 40 us time resolution. Additionally, large numbers of elves were discovered in the PIPER data, allowing for the beginning of a statistical examination of elve properties based on large-scale ground-based observation of elves. Among the elves recorded were two examples of nearly-simultaneously occurring elves, which have not been observed until now due to the lack of high time resolution and optical sensitivity needed to discriminate them.

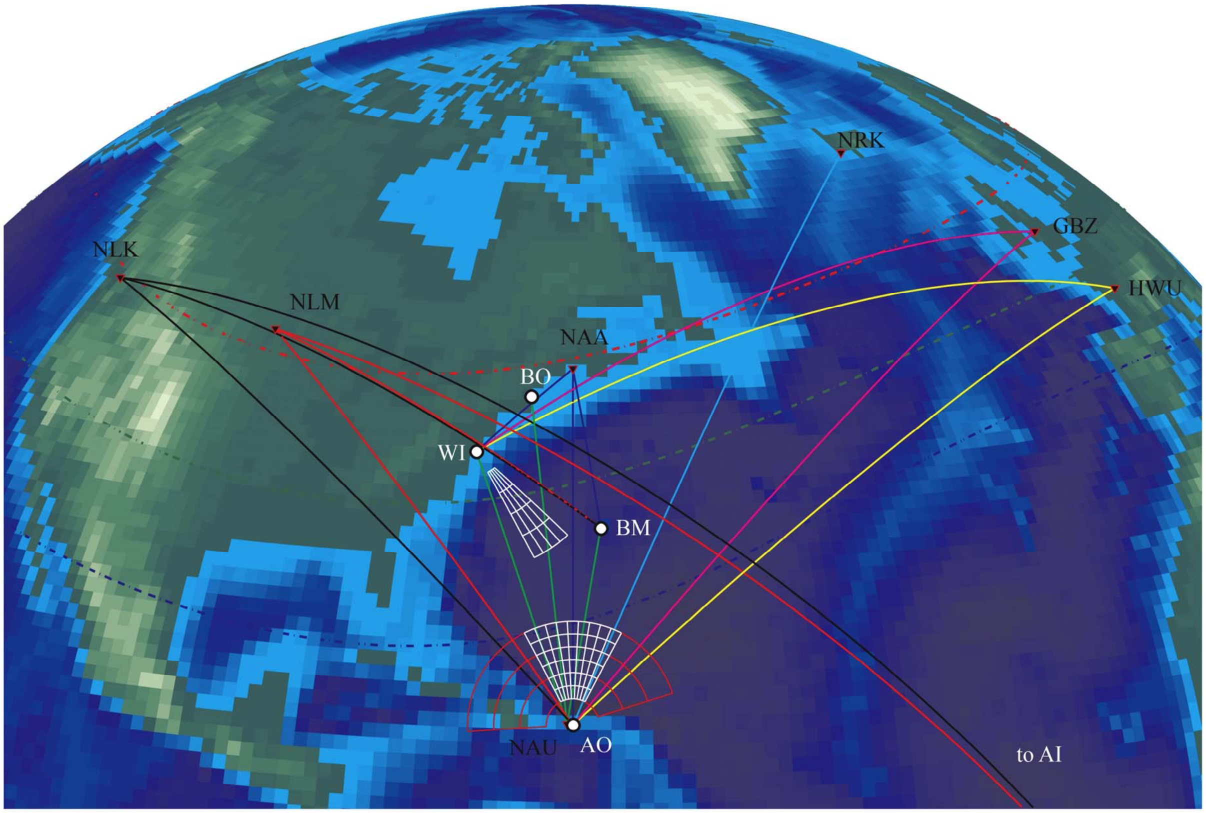

Figure 1. Optical observation viewing area in Arecibo and Wallops Island (shown in white), and monitored VLF transmitter GCPs.

Analysis of CCD sprite imaging data from the Summer 2007 TLE Observation Campaign in Yucca Ridge, CO was completed. Several sprites were observed simultaneously with PIPER and the CCD camera, allowing comparison between the high time resolution PIPER data and the high spatial resolution CCD camera data.

During the month of July, coordinated photometric and CCD observations of sprites and elves were made from Langmuir Lab, NM. These observations continued the observations from the Summer 2007 TLE Observation campaign, with a specific focus on imagine elves from sprite- and non-sprite-producing storms. Large numbers of elves were recorded (over 100 from one storm alone, and ~50 from each of the more typical storms), allowing us to continue to build our library of ground-based elve observations for statistical investigation. Additionally, coordinated sprite images from this campaign afford us the opportunity to apply our PIPER 2-D image reconstruction algorithm to form the first high-speed 2-D sprite images from orthogonal 1-D photometer observations and low-rate CCD video.

During the past year a 3D Finite-Difference Time-Domain model was developed that simulates the lightning electromagnetic pulse interaction with the lower ionosphere. This is the first model capable of simulating in-cloud lightning pulses, and the first to show the effect of the Earth's magnetic field on elves and the associated density perturbations. The model has been used to demonstrate the in-cloud

discharges may produce elves, and that bursts of these discharges may be measured as early/fast events.

RESULTS

The following scientific results were obtained and reported in the indicated papers:

Cotts et al. [2007b] discovered and studied a new and exceptional class of Early/fast events which occur during daylight hours and exhibit different characteristics than their typical nighttime counterparts. That these events are observed during daytime hours indicates that an extremely high level of ionization can be produced in conjunction with lightning. The daytime events are coincident with recorded National Lightning Detection Network (NLDN) lightning flashes (pinpointing their location), and separately recorded radio atmospherics. The daytime events are so far observed in two distinct situations. The first set of observations are perturbations on relatively short paths where the distance between the transmitter and receiver is ~400 km, with the causative lightning (and hence the likely ionospheric disturbance) within 20-50 km of the receiver. The second type of daytime Early/fast events occur on long-distance paths (>1000 km), with the causative lightning several hundred kilometers distant from the receiving site. The identified events exhibit highly directional scattering patterns including wide-angle scattering of up to 180^o indicating either a hard or a highly structured/periodic scatterer. In contrast to nighttime Early/fast events in which VLF backscatter occurs only very rarely (<5%) [Marshall et al., 2006], three of the six identified daytime disturbances exhibit wide-angle scattering. In addition 4 of the 6 events exhibit unusually long recoveries (>9 minutes). These newly identified events imply the existence of a new type of scattering source which is more likely to be observable during daylight hours. Initial modeling results indicate that significant backscatter from an ionospheric disturbance will only be observable when the scatterer is both highly conducting ($>10^4$ electrons/cm^3) and has exceptionally narrow horizontal extent (i.e. Gaussian width <2 km).

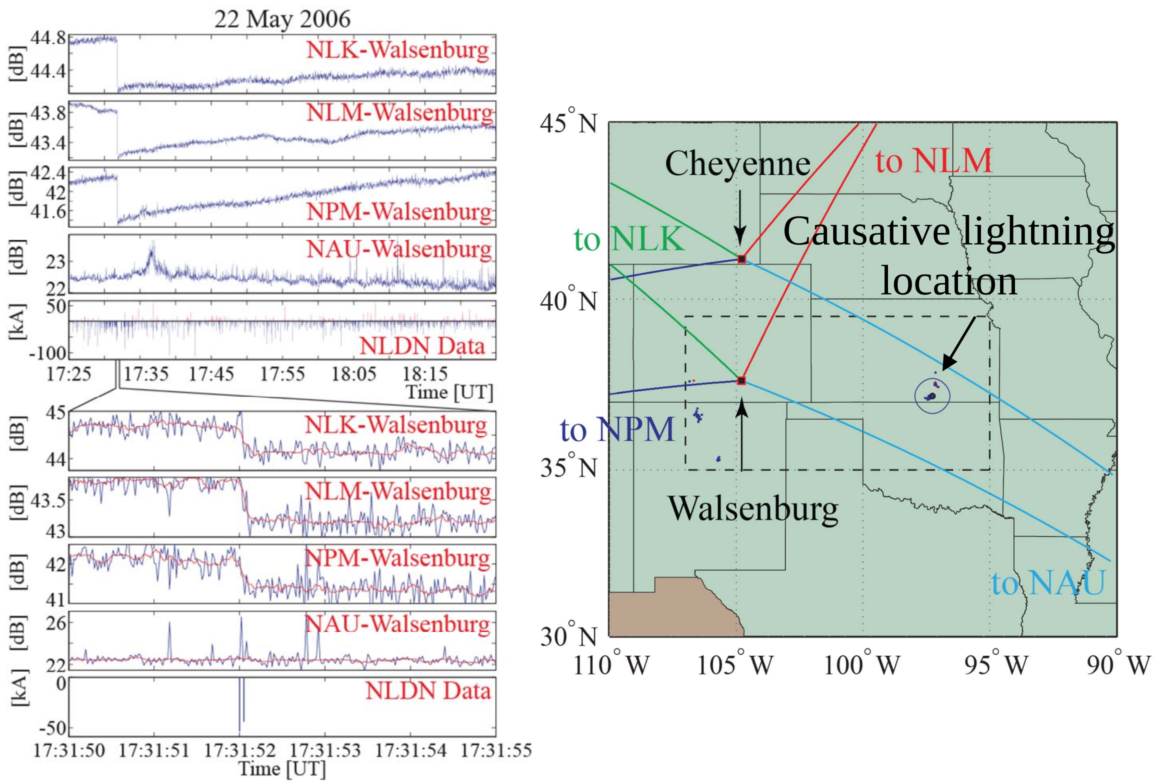

Figure 2. From Cotts et al. [2007]. (left) Daytime Early/fast event observed at Walsenburg, CO including the full extent of the events (top 5 panels) and onset of the event (bottom 5 panels). (right) Map depicting the location of the causative lightning and distribution of disturbed paths. (Note in particular the NPM-Walsenburg path which is strongly perturbed, but does not cross the causative lightning disturbance region, indicating strong backscatter).

Marshall et al. [2008b] presented the PIPER instrument as a new tool of optical remote sensing with geophysical applications. Discussions of the first observations of sprites, elves, and halos with the PIPER instrument were presented in detail, along with measurements from experiments targeting optical signatures of transmitter-induced and heater-induced electron precipitation from the radiation belts.

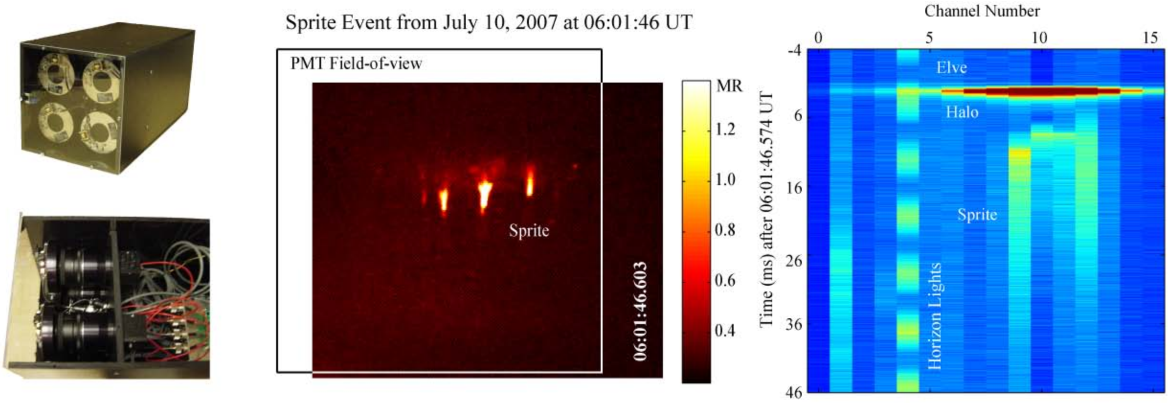

Figure 3. Adapted from Marshall et al. [2008b]. (left) The PIPER Instrument and a view of the inside of its box. (middle) A sprite observed in 2007 using an intensified CCD camera, and (right) the same sprite observed by PIPER's vertically-oriented channels, showing the discrimination of an elve, halo, and sprite in time and space.

Newsome and Inan [2008] presented the PIPER image reconstruction technique developed to form 2-D images out of the sets of orthogonal 1-D photometric observations made by PIPER. The technique involves grouping series of frames of 1-D PIPER observations along with a single corresponding frame from a low-frame-rate 2-D CCD imager, and then solving a convex optimization problem to generate the set of high-frame-rate 2-D frames that fit the observed data and minimize the measure of total variation in the frames. The technique was tested on a variety of sprite image test sequences accumulated over the years, with very promising results. Additionally, the technique was tested on a variety of test image sequence designed to spoof the algorithm, allowing us to discover at what limits the technique begins to break down.

Marshall et al. [2008a] demonstrated that so-called Early VLF perturbations may, in many cases, be caused by the in-cloud component of large cloud-to-ground lightning discharges, through the electromagnetic pulses (EMP) emitted by the short in-cloud discharges. A 3D time-domain model of the EMP effect on the lower ionosphere was developed and showed that these in-cloud EMPs can effect the lower ionospheric density through dissociative attachment to molecular oxygen and through ionization. A frequency-domain model of the subionospheric VLF transmitter propagation from Chevalier et al. [2008] was used to show that the density changes produced by bursts of in-cloud lightning can be measured as amplitude and phase changes on the VLF transmitter signal.

Marshall et al. [2008c] developed the 3D EMP model used in Marshall and Inan [2008a], and used it to quantify in detail the effects of cloud-to-ground and in-cloud lightning discharges. In particular, is was found that with the 3D capability, the Earth's magnetic field can cause an observable asymmetry to elves. Furthermore, is was shown that elves are rarely associated with ionization, but rather electron density losses due to dissociative attachment. In the case of in-cloud discharges, the effects of parameters such as altitude, angle, amplitude, discharge speed, and so forth were investigated, and a sequence of pulses was input to show that large changes to the ionospheric electron density can be caused by so-called "sferic bursts" associated with sprite-causative cloud-to-ground lightning.

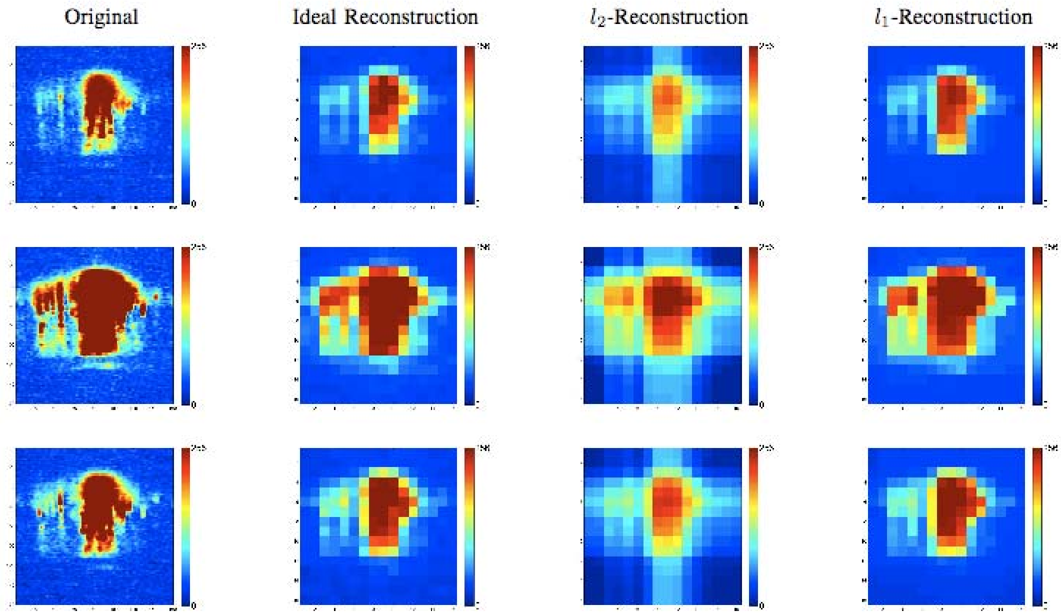

Figure 4. From Newsome and Inan [2008]. Reconstruction results for three consecutive sprite frames. Columns are, left to right, original frame image (not input to algorithm), the ideally reconstructed frame (used to score reconstruction results), reconstructed frames using minimization of an inferior metric, and reconstructed frames using total variation (l_1) minimization. The 2-D reconstructed frames on the right were constructed only from 1-D PIPER observations (the "sums of rows and sums of columns" of the frames in the left column) and a single, integrated 2-D image (the sum of all the frames in the left column).

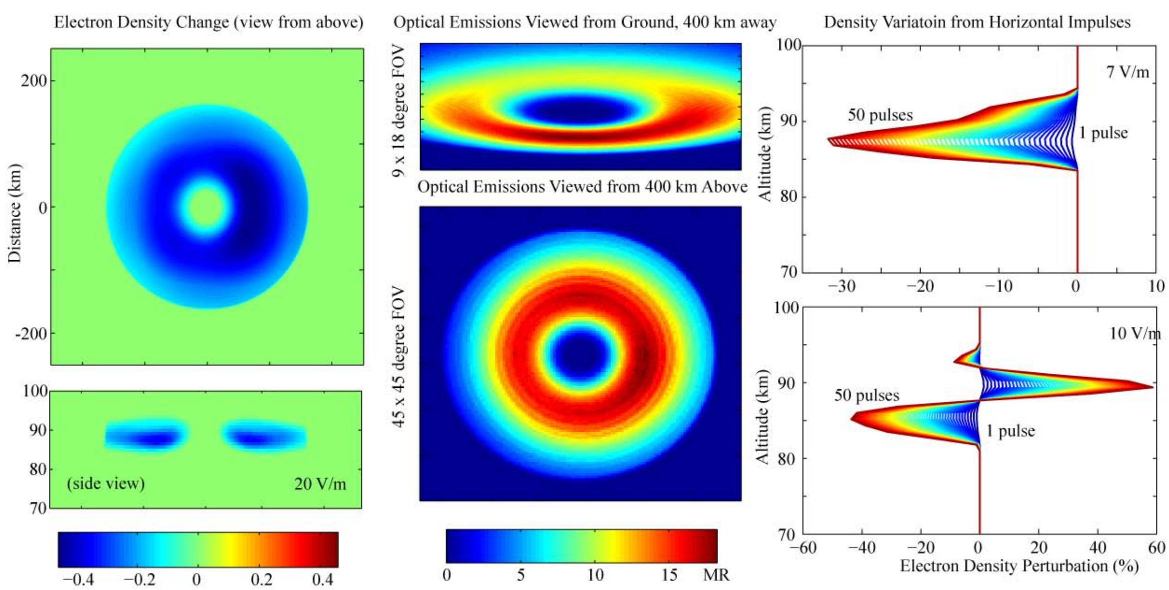

Figure 5. Adapted from Marshall et al. [2008a, 2008c]. Results from the EMP Model. (left) Density perturbation (vertical and horizontal slice) due to cloud-to-ground lightning. (middle) Associated optical emissions, observed from ground and from above. (right) 1D slices of electron density perturbation due to a sequence of horizontal impulses.

IMPACT/APPLICATIONS

The general impact of our results is the quantification of ionospheric variability (especially the mesosphere and the D region) due to both lightning discharges and radiation belt particle precipitation. VLF Holographic measurements with the HAIL system have led to the identification of the underlying structure and temporal and spatial characteristics of ionospheric disturbances associated with lightning discharges. In view of a global lightning rate of ~100 flashes per second, the contribution of lightning discharges may be globally important to both ionospheric variability and the possible role in the formation of the slot region of the radiation belts. Furthermore, our correlative studies of sprites, early/fast perturbations and associated VLF activity result in quantification of the effect of sprites and elves on the ionosphere.

TRANSITIONS

The establishment of a user-friendly web-based data viewer program (http://hailweb.stanford.edu/vlfdataviewer.html), updated daily, which allows remote access to all HAIL data and expands both our educational outreach component and facilitates our future collaborations with other researchers in the field. High school students can view 1-s resolution VLF amplitude or phase data, recorded at their host school or at any other HAIL site, and explore ionospheric effects of recent events such as solar storms, galactic gamma ray bursts, and local thunderstorms. The various MATLAB-based analysis software developed by Stanford for the HAIL research project are being used by interested high school students at the schools that house our equipment, as well as by collaborating researchers from other institutions [e.g., *Haldoupis et al.*, 2004, 2006; *Mika et al.*, 2005, 2006].

RELATED PROJECTS

The Atmospheric Sciences Division of NSF jointly funds the holographic VLF/LF measurements component of our project. Other related projects include VLF/LF observations carried out at Palmer Station, Antarctica; University of Iraklio, Crete; Firat University, Turkey; and the Centre National de la Recherche Scientifique (CNRS) in Nancay, France, which allow us to examine characteristics of these events in settings other than over the United States.

PUBLICATIONS

Cotts, B. R. T., U. S. Inan, and N. G. Lehtinen (2007a), Daytime early VLF perturbations exhibiting long recoveries and wide-angle scattering. 2007 Fall AGU Meeting, Poster AE23A-0907.

Marshall, R. A., U. S. Inan, and T. W. Chevalier (2008a), Dissociative Attachment as a Source of Early VLF Perturbations, *Geophys. Res. Lett.*, [in press, refereed].

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